A Code to Model Electromagnetic Phenomena

Livermore's EMSolve code helps scientists understand and predict electromagnetic fields.

AMONG the pantheon of great scientists, few have made contributions as far-reaching as James Clerk Maxwell, the 19th-century Scottish physicist. Maxwell's four equations unified electricity and magnetism for the first time and described light as an electromagnetic wave that varies in space and time. His equations showed how a changing magnetic field produces an electric field, and how a changing electric field generates a magnetic field. In 1931, on the 100th anniversary of Maxwell's birth, Albert Einstein described the change in the conception of reality that resulted from Maxwell's work as "the most profound and the most fruitful that physics has experienced since the time of Newton."

For decades, Livermore engineers and scientists have simulated the propagation and interaction of electromagnetic fields to better understand magnetic fusion energy, lasers, radar, nuclear weapon effects, electronics, and communication systems. Over the years, a number of commercial computer codes have appeared that solve Maxwell's equations for various engineering and physics research applications. None of the codes, however, has proved as powerful, accurate, or flexible as a Livermore code called EMSolve.

The code has been used to accurately simulate electromagnetic fields in structures ranging in size from a computer chip to a two-story building. EMSolve's

enormous simulation capabilities require that it run on parallel supercomputers. These machines feature thousands of microprocessors that share computing chores to predict and demonstrate the actions and effects of electromagnetic fields within time frames as short as 1 femtosecond (10^{-15} second).

"EMSolve is used throughout the Laboratory because studying electromagnetic fields is an important aspect of almost every Livermore program," says engineer and computational scientist Dan White, project leader for EMSolve. The code has supported research projects sponsored by the Defense Advanced Research Projects Agency (DARPA), U.S. Air Force, U.S. Navy, and Stanford Linear Accelerator Center.

EMSolve has been cited in more than 30 peer-reviewed journal articles. For example, the March 2007 cover of *IEEE Transactions on Magnetics* features a paper by White and colleagues concerning simulation of magnetic fields in complex geometries. The program has also been licensed to private industry.

White started EMSolve for his Ph.D. dissertation while working in Livermore's Student Employee Graduate Research Fellowship (SEGRF) Program. (See *S&TR,* June 2006, pp. 4–11.) He devised the code to simulate electromagnetic fields using finite-element analysis, a common simulation technique in which a volume is divided into an assemblage of thousands or even millions of simple elements. The changing fields within each element are then calculated. Visually, the collection of elements resembles a wire mesh.

Structured and Unstructured Meshes

The most common method for electromagnetic simulation uses a structured type of mesh to model a geometry of interest. A structured mesh arranges mesh nodes in parallel planes. Such an arrangement works for typical problems but is inadequate for many

research applications at Livermore. With EMSolve, researchers can solve Maxwell's equations on an unstructured mesh, which uses elements of simple shapes such as triangles or tetrahedrals in irregular patterns. Because EMSolve is based on unstructured mesh finite-element technology, the code excels at modeling problems with complex geometries containing curved surfaces.

"The code is robust and takes a rigorous approach to solving problems," says White. "It can generate structured meshes for straightforward electromagnetic simulations and unstructured meshes for the enormous simulation challenges Livermore researchers face every day."

Since the code's first release in 1997, it has been continually improved, with funding from Livermore's Laboratory Directed Research and Development Program, the Engineering Directorate, and outside sponsors. Most code advancements, including new algorithms and additional physics, have been done by graduate students. White says, "Ph D. students bring important new ideas about what we can incorporate into the code." Joe Koning, Rob Rieben, and Aaron Fisher, now Livermore employees, based their dissertations on developing new EMSolve capabilities while at the University of California (UC) at Davis. Other contributors include Livermore physicist Niel Madsen, former Livermore postdoctoral researchers Paul Castillo and John Rockway, retired UC Davis professor Garry Rodrigue, and former University of Washington Ph.D. student James Pingenot.

The current development team consists of White and colleagues Mark Stowell and Ben Fasenfest. Stowell is a computer scientist who develops the complex algorithms and data structures required for parallel computations. Fasenfest is an engineer who specializes in EMSolve applications.

EMSolve is one of several codes developed by Livermore engineers. "Livermore's computational engineering community is among the best in the world at solving very large and nonlinear structural and electromagnetic applications," says Robert Sharpe, who leads the Computational Engineering focus area. "Our engineering analysts have expertise in areas such as code development, numerical methods, parallel processing, and material behavior. The development of new codes is driven in part by the increasing expense to execute a comprehensive suite of physical experiments. More and more, we're doing experiments virtually. Because of the codes' proven accuracy, we have confidence in the results."

Sharpe notes that commercial codes are not applicable to the unusual electromagnetic problems encountered in Livermore research. "Our needs go well beyond the scope of codes we can obtain commercially," says Sharpe. Neither can commercial codes be used on the latest massively parallel computers installed at Livermore. "We have the computational resources to explore questions other researchers can't," says Sharpe. Also, he notes, while most commercial codes can make assumptions about physics that are "good enough" for many applications, such assumptions can skew results at the level of detail Livermore researchers require.

EMSolve is used to model events that occur on extremely short timescales. For example, simulations involving a light wave traveling 300 meters in a millionth of a second often require thousands of consecutive time steps, each separated by a few femtoseconds.

Because Maxwell's equations solve for both electric and magnetic fields, EMSolve supplies information on both fields simultaneously. A major challenge is how to visually display the massive amount of data the code supplies. The

EMSolve team works closely with the Livermore computer experts who developed VisIt, a visualization tool that analyzes huge amounts of data generated by supercomputer simulations, to present the code's findings in ways that are readily understood. (See *S&TR*, October 2005, pp. 10–11.) The code also uses software libraries developed at Livermore's Center for Applied Scientific Computing.

One of the EMSolve's most useful features is an error estimator that functions like a self-diagnostic mechanism. The error estimator shows a user those areas in the mesh where the simulation results are not sufficiently resolved. The user can then increase the mesh density to reduce the error. This feature decreases the number of required iterations and makes possible more accurate solutions with less computing power.

Far-Ranging Applications

The code has been used to study optical trapping of microparticles, linear particle accelerator components, photonic and electronic devices, aerospace and radar systems, microelectronics devices, radar interrogation of buildings, electromagnetic interference, and cell-phone transmission. EMSolve also supports Livermore's national security missions in stockpile stewardship, homeland security, and the National Ignition Facility (NIF).

The EMSolve team has performed several studies for DARPA. In collaboration with researchers at the University of Washington, the team simulated electromagnetic waves traveling through an integrated chip containing both digital and analog components. These chips can be found in cell phones and other devices that transmit data. "Digital components generate noise and can interfere with the functions of analog components," says White. "We want to understand electromagnetic interference on the circuits of these chips." The simulations introduced noise consisting of a 5-gigahertz radio-frequency signal and tracked how fast and far the signal propagated through the circuit.

Another DARPA project involved simulating the behavior of radar waves inside a building. Radar uses electromagnetic waves to detect and image objects and to determine their distance from an observer. In principle, a radar system with advanced computer processing of reflected signals could determine a building's internal structure. "We're helping DARPA to better understand the complex radar-scattering mechanisms that occur inside buildings," says White.

The simulation team focused on a generic two-story structure with about 465 square meters (5,000 square feet) of interior floor space with doors, windows, hallways, several rooms, and a stairwell. In one simulation, the structure was made of solid concrete, and in another, it was constructed with cinder block and rebar. The virtual building measured 22.6 meters long by 10 meters wide by 6.75 meters tall. Simulated electromagnetic fields were generated by a radar source outside the structure near the broad side and then the narrow side of the building. The hypothetical radar was a broadband pulsed system with a high frequency of 1 gigahertz and a center frequency of 700 megahertz.

The computational mesh elements varied between 0.75 and 1.4 centimeters on each side. The mesh consisted of more than 10 billion elements, comprising one of the largest electromagnetic simulations ever performed. The simulations, done on

(a)

(b)

10 micrometers
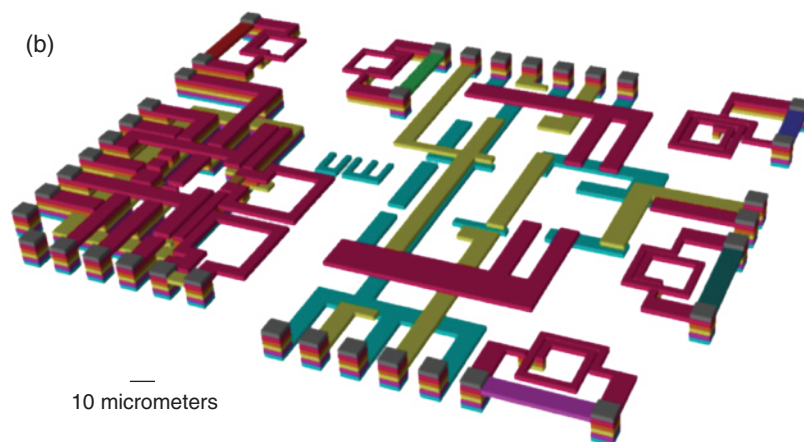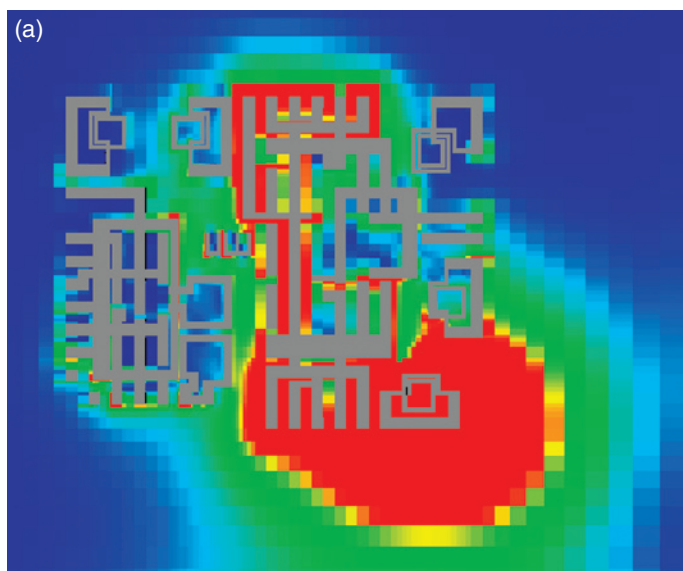
(a) An analysis using the EMSolve code studied noise in integrated circuits containing both digital and analog components. In this simulation, red denotes the highest magnitude and blue the lowest of the electric current in the substrate. (b) A magnified view shows the three-dimensional structure of the chip.

Livermore's Zeus machine, used 1,536 of Zeus's 2,304 processors. The calculations were run long enough for the radar pulse to travel 30 meters when the transmitter was located on the broad side and 50 meters when it was on the narrow side. These distances corresponded roughly to the distances from the transmitters to the farthest corner of the building and back.

The simulations revealed how wall composition affects the propagation of radar waves. Although some of the

(a)

(b)

(a) EMSolve simulated the interaction of radar waves inside a hypothetical two-story building. (b) A snapshot captured 140 nanoseconds after the launch of the radar wave shows the electric-field plane through the center of the first floor. The small red block is the stairwell, which tends to trap electromagnetic energy.

radar waves were reflected from the outside wall of the building, a significant amount penetrated into the building. Rebar and cinder block walls trapped electromagnetic fields within individual rooms, while concrete walls tended to trap fields within walls and ceilings. The trapped fields in the concrete structure lagged behind the initial pulse because the wave speed within concrete is only 40 percent of the speed of light in air. Another phenomenon, especially evident in continuous concrete, was a wave-guiding effect in which radar waves seemed to be pulled along the building's central corridor toward the far side.
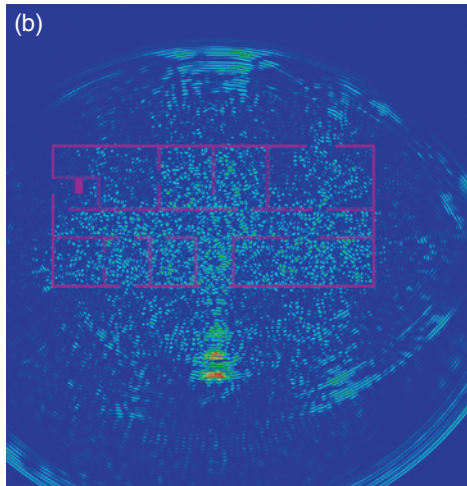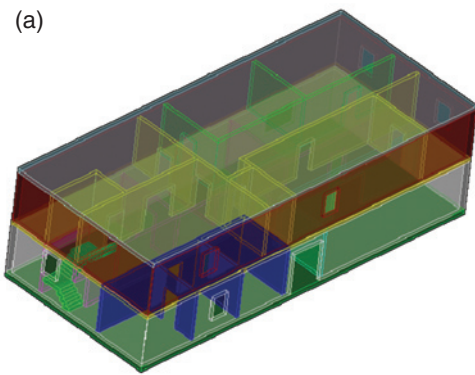
Tracking Light in a Crystal

The Livermore team has also studied the three-dimensional (3D) electromagnetic field intensities of photonic band-gap (PBG) crystals, also called photonic crystals. A revolutionary concept for guiding light, PBG crystals consist of alternating layers of various insulating materials. The devices can stop the propagation of light, allow propagation only in certain directions, localize light in certain areas, or prevent the transmission of light within a certain frequency range.

While a graduate student, Rieben used EMSolve to provide the first-ever 3D

simulation of light in a PBG crystal. He modeled PBG structures operating at 11 gigahertz and measuring 1.1 by 1.1 by 1.2 centimeters. The crystal was arranged in a 90- by 13- by 7-layer configuration of aluminum oxide cylinders. The simulations tracked the propagation of signals making two separate 90-degree bends in three dimensions, which were made possible by three defects introduced in the crystals. The finite-element structured mesh consisted of 419,328 hexahedral elements. Within each element, the electric field was represented by a cubic polynomial. In contrast, other simulations assume only linear variations. The simulations ran for 6,500 time steps, with each step separated by 300 femtoseconds.

The EMSolve team also simulated the operation of an induction cell, which is used to accelerate a beam of electrons in a linear accelerator. The simulation, done for the Stanford Linear Accelerator Center (SLAC), was conducted as part of the design effort for the International Linear Collider (formerly called the Next Linear Collider). A global collaboration of particle physics laboratories, including Livermore, is involved in designing the machine, which will collide electrons with positrons to produce exotic subatomic particles. (See *S&TR*, September 2004, pp. 22–24). SLAC

(a) Stairwell

(b) Stairwell
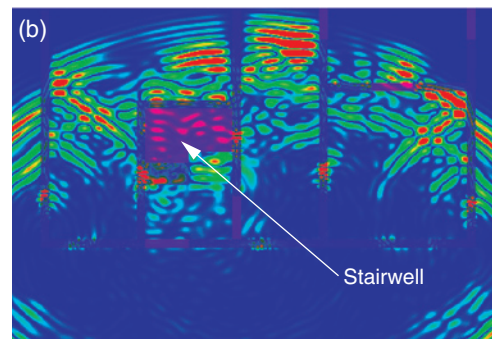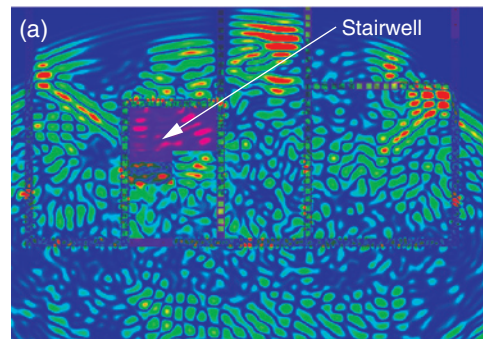
These close-up views show EMSolve simulations of a building made of (a) rebar and cinderblock and (b) solid concrete. The rebar and cinderblock walls trap fields within individual rooms, whereas the concrete walls tend to trap fields within walls and ceilings. In the solid concrete building, an inner-wall wave-guiding effect is evident. In both cases, electric fields accumulate in the stairwells.

computational scientists have recently built on EMSolve software to create a version tailored for their physics research.

Modeling Electromagnetic Pulses

EMSolve is used increasingly in Livermore programs. One of the most challenging applications for EMSolve is advancing the understanding of electromagnetic pulses (EMPs), which result from laser–target interactions in high-power laser facilities. An EMP is an intense burst of electromagnetic energy caused by an abrupt, rapid acceleration of electrons. The burst lasts 10 to 1,000 times longer than the original laser pulse.

Researchers have reported many cases of EMP-induced diagnostic damage and data loss at short-pulse, high-energy laser facilities even when instruments have been isolated and shielded. Because of this damage, scientists want to improve their understanding of EMPs for current laser facilities and for the next generation of short-pulse, high-power lasers, including NIF, France's Laser Megajoule (LMJ), and a new short-pulse capability

at the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics. Effective mitigation techniques require detailed data on the properties of EMP and the mechanisms by which it is produced.

The main source of strong EMPs at laser facilities is believed to be the small fraction of electrons—produced by laser–plasma interactions—that escape the target. As the electrons exit, they leave behind a positively charged target, thereby creating a strong electrostatic field that causes electron currents from throughout the chamber to flow and neutralize the positive charge. The electrons hit the target chamber wall, creating an EMP, which induces currents to flow back and forth. Physicist Dave Eder, group leader for facility modeling at NIF, compares the target chamber to a violin string that rings after being plucked.

Scientists are obtaining the first quantitative understanding of EMP processes from a laser by using the Titan laser at Livermore's Jupiter Laser Facility. Researchers measure the number of escaping electrons, the time and spatial

distribution of the electrons, the EMP, and the resulting transient currents. The recorded properties of the electron stream are compared to 3D EMSolve simulations of the same experiments. In this way, they are validating the code's accuracy and effectiveness as a tool to predict the strength, duration, and electromagnetic frequency of EMPs generated on Titan and other laser facilities. The effort is funded by the Laboratory Directed Research and Development Program and is an Engineering Directorate technology-base project.

"We're developing a predictive simulation capability that can be applied to existing and future laser facilities to mitigate EMPs and greatly reduce the occurrence of diagnostic upset or damage and data loss," says Eder. Scientists hope to use the simulations to develop ways to reduce EMP for a wide range of target–laser conditions. Mitigation options include reducing the number of electrons escaping, installing shields that the electrons strike before they impact the target chamber walls, and developing new grounding and shielding configurations for instruments that are sensitive to EMP.

The EMSolve simulations shown on p. 9 begin with a detailed 3D model of the Titan target chamber, which is crowded with optical stands. The simulations depict electromagnetic fields flowing from the moving electron pulse as it speeds to the chamber wall, inducing currents to flow throughout the chamber. In these depictions, which represent a "slice" through the 3D data, red indicates the strongest magnetic fields while blue shows a zero magnetic field. A portion of the electron stream can be seen striking the top of a metal post supporting an experimental target. The suddenly positively charged stand is then neutralized by electrons coming up from the table that supports the experimental target.
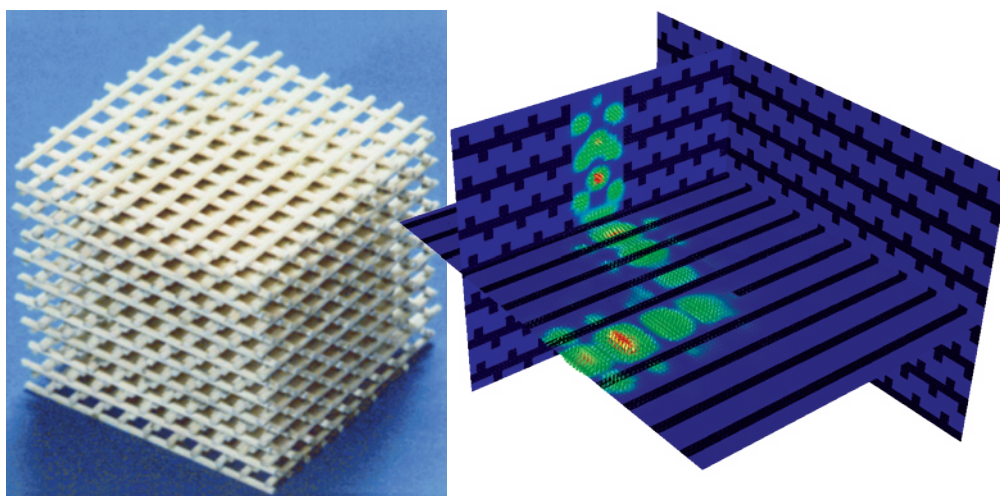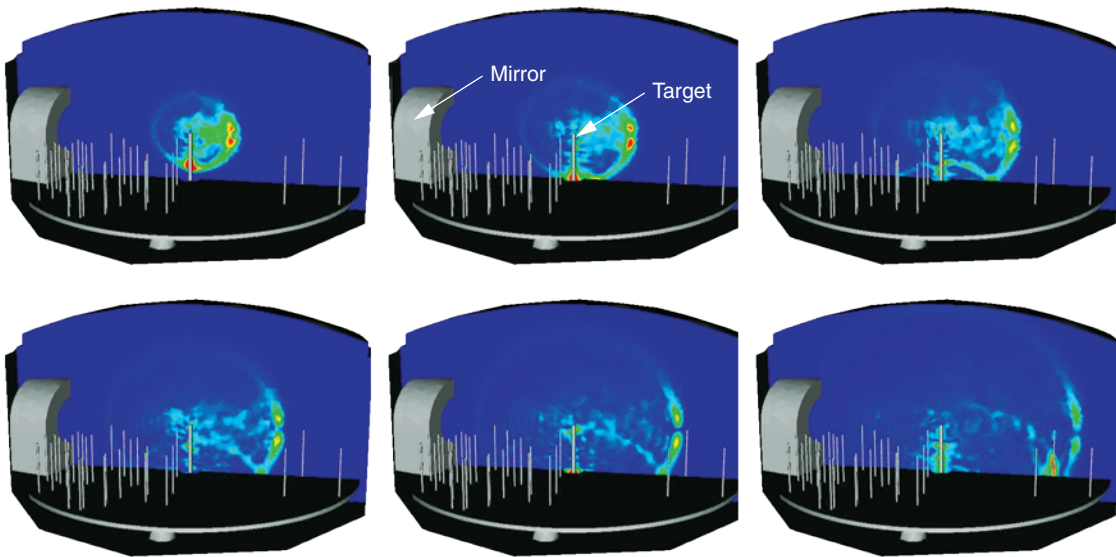

The first three-dimensional EMSolve simulation of light in a photonic band-gap crystal tracked the propogation of signals as they made two separate 90-degree bends.
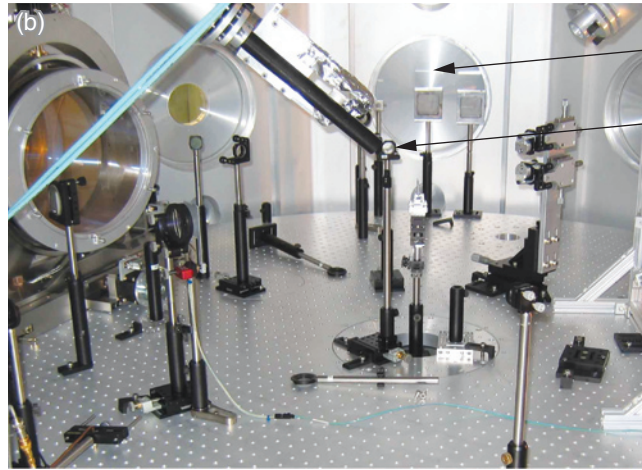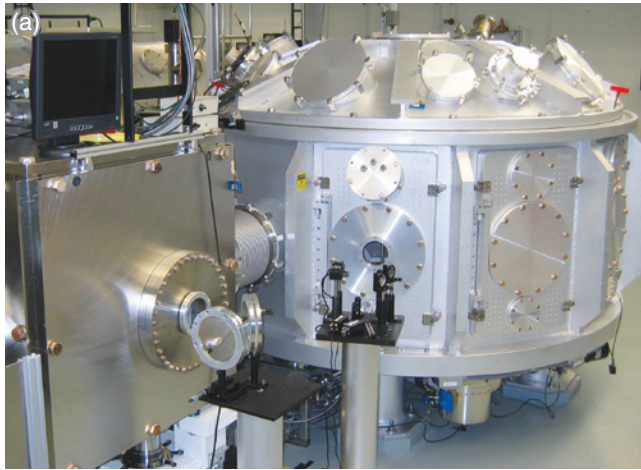
Photos of the Titan laser target chamber show the (a) exterior and (b) interior of the chamber.

This EMSolve simulation shows the electromagnetic pulse generated by high-energy electrons streaming from the Titan laser target in time intervals separated by several picoseconds. The pulse travels from left to right, eventually hitting the target chamber wall (not shown). The stalks represent stands for diagnostic instruments and mirrors. The large curved object at left represents a mirror that directs the laser beam onto the target.

Eder is hopeful that the simulation capability can be applied equally successfully to planning experiments on other laser facilities, including NIF and LMJ. The NIF target chamber has stainless-steel louvers about 10 centimeters in length designed to reduce the amount of ablated material generated in fusion experiments. Fine structures in the target chamber, such as louvers and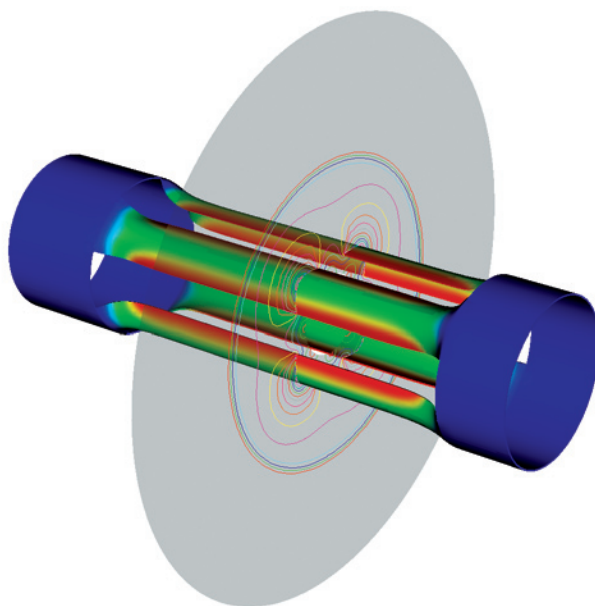 stands, affect high frequencies. As a result, Eder hopes to use EMSolve to model the effects of NIF louvers on EMPs. LMJ, currently under construction, will use louvers made of aluminum.

Building More Comprehensive Codes

White notes that some solid mechanics codes have grown into "multiphysics" codes, with the addition of fluid dynamics, heat transfer, and chemistry. Multiphysics codes are needed for stockpile stewardship to ensure the safety, performance, and reliability of the nation's nuclear weapons. However, most multiphysics codes do not yet solve for Maxwell's equations. Such a capability would make possible electro-thermal-mechanical (ETM) simulations, which have long been sought by engineers and scientists. An ETM simulation includes electromagnetics, heat transfer, and nonlinear mechanics (deformation of materials and friction).

This coupled electro-thermal-mechanical simulation shows a current pulse generating magnetic pressure through a 7.5-centimeter-diameter tube. The magnetic field is so intense that it crushes the tube. The solid colors represent the velocity at which it is being crushed, with red being the highest. The contour plot shows the magnitude of the magnetic field.

microelectromechanical systems—tiny devices that integrate mechanical elements, sensors, and electronics on a silicon substrate. Sharpe notes that ETM codes will be required to accurately simulate Office of Naval Research railgun experiments. A railgun works by sending electric current along parallel rails, creating an electromagnetic force so powerful it can fire a projectile at tremendous speed. Future U.S. Navy ships may use stored electromagnetic energy to power railgun-launched offensive and defensive weapons. Livermore researchers are also interested in railguns as a possible technology for achieving velocities and pressures beyond those of Livermore's two-stage gas guns.

White predicts that EMSolve will continue to grow in adaptability, accuracy, and capability. The code is sure to play an important role in Livermore scientists' and engineers' exploration of the electromagnetic fields critical to advancing countless research programs.

—*Arnie Heller*

Because EMSolve is based on a modular software architecture, the core finite-element technology can be readily incorporated into other codes to produce ETM simulations. For example, the team has added several EMSolve modules into ALE3D, which models the response of materials to heat and explosives and other processes. The code can also model potential glass damage mechanisms in NIF, which is the most energetic laser system in the world as well as the largest optical instrument ever built. The giant laser has 7,500 large optics and more than 30,000 small optics, all of which can slowly accumulate damage from repeated firings. Physicists believe that EMSolve, coupled with ALE3D, one

of Livermore's hydrodynamics codes, can help them better understand the mechanisms of glass damage and point the way to mitigation strategies.

The team has also added EMSolve modules to Diablo, a new Livermore 3D solid mechanics code developed for long-duration stockpile-stewardship-related simulations. In addition, EMSolve finite-element modules have been incorporated into HYDRA, a radiation–hydrodynamics code developed by Livermore's Inertial Confinement Fusion Program to simulate laser–plasma interactions.

Other ETM applications include electromagnetic launchers, inductive heating and mixing of metals, and